maximum input torque	115 N.m				
maximum speed	6000 r/min				
center distance	72mm				
speed ratio of shift	1	2	3	4	5
	3.55	2.05	1.35	1	0.769

2.5 Vehicle dynamic module

The longitudinal dynamic model of the vehicle was built to calculate the longitudinal acceleration, velocity and displacement based on vehicle driving force and driving resistance force[11]. The driving resistance force is composed of rolling resistance force, air resistance force, climbing resistance force and so on.

2.5.1 Driving force of vehicle

Driving force of vehicle is expressed as following:

$$F_t = \frac{T_{td}}{r} = \frac{T_e i_g i_0 \eta}{r} \tag{11}$$

where T_{td} is the driving torque that works on the driving wheel, r the rolling radius of the wheel, η the mechanical efficiency of the transmission system, i_g the transmission ratio, i_0 the main reducer transmission ratio.

2.5.2 Vehicle driving resistance force

The vehicle longitudinal resistance force includes rolling resistance force F_f , air resistance force F_w , acceleration resistance force F_j and climbing resistance force F_i . Its expression is shown as below:

$$\sum F = F_f + F_w + F_j + F_i \tag{12}$$

F_f is related to the tire load, the type and the pavement condition. Its expression is shown as below:

$$F_f = Gf\cos\theta \tag{13}$$

where G is the total weight of the vehicle in N, f the rolling resistance coefficient, and θ the ramp angle respectively.

F_w is expressed as below:

$$F_w = \frac{C_d A \rho v^2}{2} \tag{14}$$

where C_d is the air resistance coefficient; A is the automotive frontal area in m^2 ; ρ is the air density in kg/m^3 and v is the running speed of the vehicle in m/s.

F_j is expressed as below:

$$F_j = \delta m \frac{dv}{dt} \tag{15}$$

where δ is the vehicle rotary mass coefficient and m is the vehicle quality in kg.

F_i is expressed as below:

$$F_i = G\sin\theta \tag{16}$$

The vehicle acceleration of a is shown as below:

$$a = \frac{dv}{dt} = \frac{F_t - F_i - F_f - F_w}{\delta m} \tag{17}$$

vehicle speed is expressed as below:

$$v = \int_0^t a dt \tag{18}$$

3 Shift rules

The shift rule is used to determine the shifting time of vehicles, and it can reflect drivers' handling intention and fit different running environment. The shift rule directly influences the dynamic performance, economic performance and emission performance of the vehicle.

3.1 Fundamental shift rules

Vehicles operate with different state parameters, and the optimal shift schedule of vehicles is determined according to certain principles of performance parameters optimal. Many vehicles select best shift timing when the vehicle operates on the best power or economy performance. The following will pay more attention to introduce the process of establishing optimal power performance shift schedule.

To ensure optimum dynamic performance of vehicles, the intersection of two adjacent gear accelerations should be selected as the best dynamic shift points in a dynamic operation condition. The intersections of two adjacent gear accelerations with different throttle opening were connected and form a curve, and the curve is just the optimal dynamic shifting characteristics. If it was converted to its corresponding $\alpha - v$ curve, we will get the best dynamic up-shifting schedule.

Based on the dynamic shifting schedule and vehicle dynamic driving equations, the following equations can be obtained as:

$$\frac{dv_{N,\alpha_n}}{dt} = \frac{dv_{N+1,\alpha_n}}{dt} \tag{19}$$

$$\frac{dv_{N,\alpha_n}}{dt} = \frac{g}{\delta_N G}\left[F_{t(N,\alpha_n)} - F_w - F_i - F_f\right] \tag{20}$$

$$\delta_N = 1 + \frac{g\sum J_w}{Gr^2} + \frac{g(J_e + \lambda)}{Gr^2} i_0^2 i_{g,N}^2 \eta \tag{21}$$

where v_{N,α_n} and v_{N+1,α_n} are the vehicle speed of the Nth gear and $N+1$th gear respectively when the throttle opening is α_n ; δ_N is the rotary mass coefficients of Nth gear affected by the engine characteristics; $F_{t(N,\alpha_n)}$ is the vehicle driving force of the i gear; J_e and J_w are the inertia which connected to the engine flywheel and the rotational inertia of the wheel respectively; λ is the decreasing coefficient of the engine in a unsteady state engine, and $i_{g,N}$ is the transmission ratio of the Nth gear.

The optimal dynamic up-shifting curve can be obtained by solving above equations. The solved curve is as shown in Fig.3. In the practical application, it should be considered that a slight speed decline caused by the power interruption for shifting. The rate of decline differs with the vehicle speed.

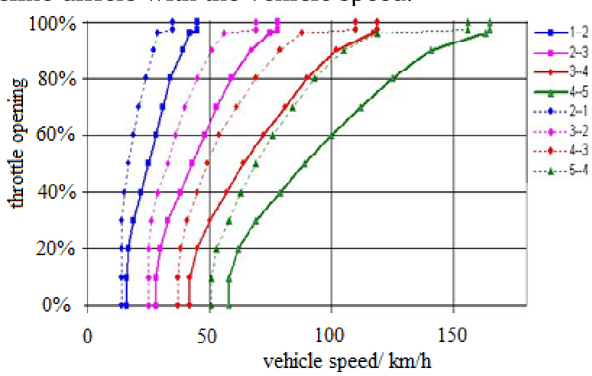

Fig.3. Optimal dynamic up-shifting curve

The drop point is selected and calculated based on its regular up-shifting schedule and selection of convergence degree, and 5km/h is selected in this paper. And at the same time, down-shifting speed of the N gear must be equal to or greater than the minimum speed of the N gear to prevent engine to misfire.

3.2 Comprehensive shift rules

The outlined above about the fundamental shift rules is based on dynamic principle, which consider more about optimal performance area in a steady state for the engine and can not meet the requirement for driving. In this paper, the revised shift rules are formulated which also consider the dynamic performance in a dynamic operating condition and various influencing factors about human-vehicle-road[12]. The influence of various factors on the shift rules is as shown in Fig.4.

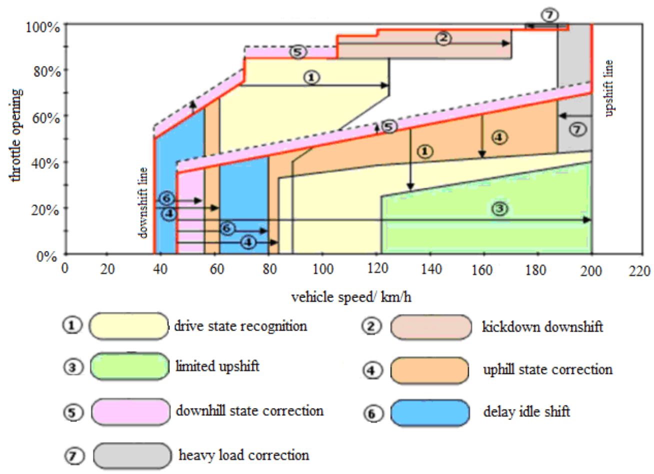

Fig.4. Influence of various factors on shift rules for driver characteristics

Fig.5 is the diagram for fuzzy reasoning about driving steering behavior characteristic. The recognition for driving steering behavior characteristic is a fuzzy reasoning process. According to parameters of throttle opening, throttle opening change rate and vehicle acceleration, the driving steering behavior characteristic is expressed by a quantifiable parameter through fuzzy reasoning. This quantifiable parameter is used to determine what type the driver is and then revise the fundamental shift rule, thereby getting the ideal control effect.

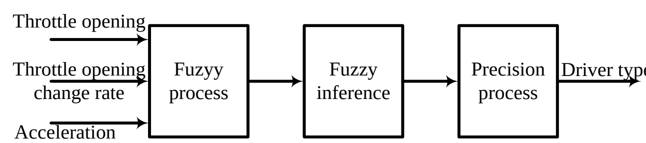

Fig.5. Diagram for fuzzy reasoning about driving steering behavior characteristic

The shift rule for the running condition mode is determined by adopting weight correction method. Conditions meeting each shift mode are designed firstly according to the measured parameters by sensors, and then the weights of shift table for different modes are determined. The weight with high priority is first selected as long as it satisfied the shift condition. There are three influence factors for the design of the weight. They are shift process risk level, shift intensity and vehicle performance influence factor. The influence of each factor is evaluated and its weight is determined. So the shift priority is then calculated and the reasonable shift rules are obtained.

The calculation of the shift priority is based on the expression of (22).

$$Q = \sum \varphi \times \psi \qquad \varphi \in (1 \sim 10), \psi \in (0 \sim 1) \tag{22}$$

where φ is the shift influence intensity, ψ is the influence factor weight, and Q is the shift priority degree.

The shift rule can be determined according to the selection logic for shift mode. Parts of the shift mode priority and their calculation are showed in table 3.

Table 3 Shift mode priority

shift mode	danger intensity		influence factor		shift intensity		priority degree	
	φ	ψ	φ	ψ	φ	ψ	Q	
thermal mode	8	0.2	2	0.5	1	0.9	3.5	5
curve mode	6	0.2	3	0.5	2	0.9	4.5	4
uphill mode	4	0.2	4	0.5	3	0.9	5.5	3
dynamic mode	1	0.2	7	0.5	7	0.9	10	2
economic mode	0.5	0.2	8	0.5	9	0.9	12.2	1

Based on the design method for shift rules, the shift rules for various modes can be worked out according to the whole vehicle parameters. The shift rules for uphill mode are as shown in Fig.6.

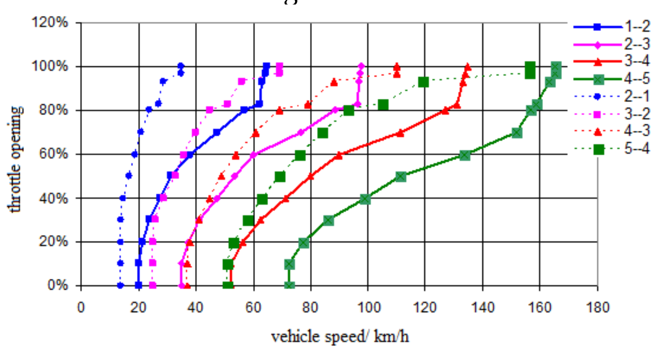

Fig.6 Shift rules for uphill mode

4 Fuzzy control technology of the magnetic powder clutch

Because of various driving conditions, driver's intention is not always constant .While the proportional control strategy cannot be satisfied with the starting requirement under various conditions, and fuzzy control algorithm was widely applied to the start and shift control of magnetic powder clutch for it can adapted to complex conditions.

4.1 Starting fuzzy controller for magnetic powder clutch

The starting control strategy for magnetic powder clutch is to realize two goals[9]:

The first goal is to ensure that the engine operates stably. It needs to determine the initial excitation current of magnetic powder clutch, which determines the initial output torque for the engagement of magnetic powder clutch. If the torque is lower than the engine load, it is easy to cause too fast rise of the engine speed and too large of speed difference, which is not conducive to clutch synchronous. But if the torque is larger than the engine load, it is easy to cause the engine speed too low and even misfire. Therefore, the initial excitation current should be determined according to throttle opening signal and engine speed signal. Because the engine speed may reflect the engine load and influence the sliding friction work, the speed is taken as the primary control parameter for the engagement control.

The second goal is ensure the ride comfort of clutch engagement. To achieve this goal, the growth rate of the excitation current of magnetic powder clutch should be controlled before it reaches the rated current. Therefore the excitation current growth rate should be determined based on throttle opening signal and speed difference signal (Δn) of driving and driven parts of magnetic powder clutch. If the throttle opening is small, the growth rate of excitation current may be less and the vehicle starts smoothly. When Δn reaches the maximum value, the engagement impact may be the largest. So at this time, the excitation current growth rate should be decreased. Along with the reduction of Δn , the excitation current growth rate will rise. When Δn reduces to zero, the excitation current growth rate may rise to the maximum with no impact.

The starting fuzzy controller for magnetic powder clutch includes initial excitation current fuzzy controller, and excitation current growth rate fuzzy controller. The input variables of initial excitation current fuzzy controller are the throttle opening α and the engine speed n_e , and the output variable is the initial excitation current I . The input variables of the exciting current growth rate fuzzy controller are throttle opening α , the speed difference Δn of clutch drive part and driven part, and the output variable is excitation current growth rate $\dot{I}$. The input variables of α , n_e and Δn are the 7-grade fuzzy set, and their fuzzy subsets for α , n and Δn may be expressed as $\alpha = n_e = \Delta n =$ {VS, S, LS, M, LB, B, VB}. The output variables of I and are also the 7-grade fuzzy set, and their fuzzy subset for I and may be expressed as $I = \dot{I} =$ {VS, S, LS, M, LB, B, VB}. The used fuzzy language control rules is if-then algorithm. The fuzzy reasoning rules for the initial excitation current are as shown in table 4, and the fuzzy reasoning rules for excitation current growth rates are as shown in table 5.

Table 4 Fuzzy reasoning rules for initial excitation current

α	n	I
VS		VS
S		S
LS		LS
M		M
LB		LB
B		B
VB		VB
	VS	VS
	S	S
	LS	LS
	M	M
	LB	LB
	B	B
	VB	VB

Table 5 Fuzzy reasoning rules for excitation current growth rate

α	Δn	$\dot{I}$
VS		VS
S		S
LS		LS
M		M
LB		LB
B		B
VB		VB
	VS	VB
	S	B
	LS	LB
	M	M
	LB	LS
	B	S
	VB	VS

4.2 Shift process control for magnetic powder clutch

Separation and engagement of magnetic powder clutch are included in shifting process. In the shifting process, the vehicle's power performance will suffer due to the separation and engagement of magnetic powder clutch. If the power interruption time is too long, the acceleration performance and ride comfort in low gear of vehicle will be affected. In addition, the automatic control performance of magnetic powder clutch is important for shifting schedule action in the shifting process. The operation of magnetic powder clutch must be coordinated with shifting action, which relates to the real-time and accuracy for the shift process and is a crucial part for the shifting research.

The separation control of magnetic powder clutch is simple in the shifting process. When it need shift, the magnetic powder clutch would be cut off the power and the control current quickly dropped to zero.The separation should be swift and sweeping so that cut off the power transmission quickly.

The engagement control of the shifting is similar to that of starting of magnetic powder clutch. The speed of different driven parts does not increase gradually from zero to the maximum. Therefore, the gear engagement control strategy is consistent with that of the starting. In the shifting process, the exciting current and its change rate of magnetic powder clutch are also controlled according to the parameters of throttle opening α, engine speed n_e and speed difference Δn between drive part and driven one of clutch.

5 Vehicle performance simulation

In order to verify the comprehensive shift rules for MAMT and the fuzzy controller for the magnetic powder clutch, the model of whole vehicle with MAMT was set up. The model was simplified on the premise of no influence on vehicle function. The simplified simulation system includes the following modules: the power transmission system module （including engine, magnetic powder clutch and transmission), the vehicle dynamics module, the best shift schedule module, the magnetic powder clutch control module, driving condition module and driver module.

5.1 Driving condition module

The selected running conditions for the performance simulation of whole vehicle are 15-condition, acceleration condition with throttle opening of 80% and a certain random condition. The 15-condition method includes four cycles, and the 15-condition curve is as shown in Fig.7. Each test cycle includes 15 different loads and speed such as idle, acceleration, constant speed, deceleration, etc. The changes of vehicle speed and throttle opening under a specific random condition are shown in Fig.8.

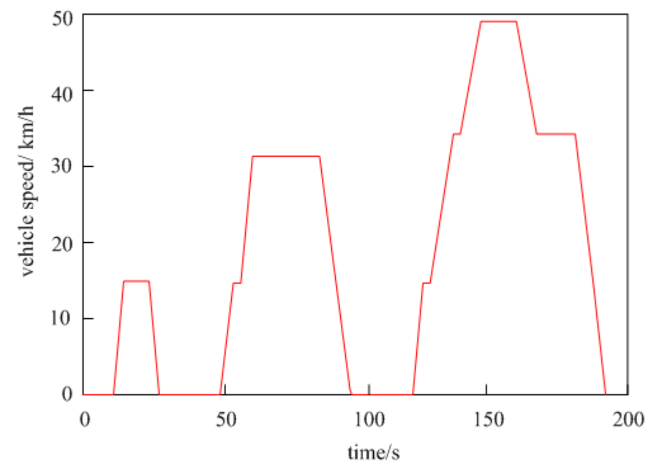

Fig.7. 15-condition curve

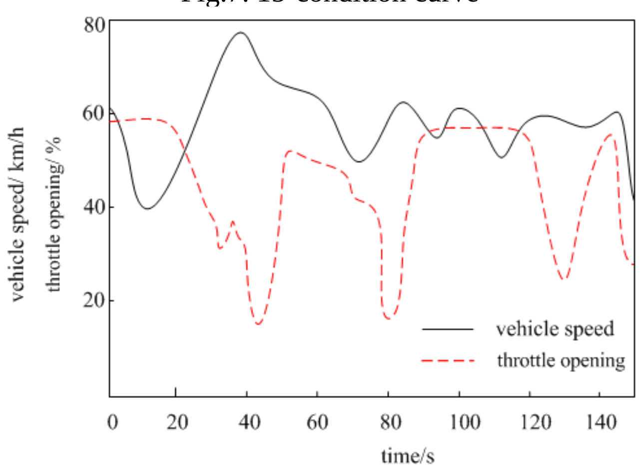

Fig.8 Changes of vehicle speed and throttle opening under a specific random condition

5.2 Driver module

The driver module include throttle controller module and brake controller module[11]. In this paper, PID controller is designed to control throttle. The throttle controller can be expressed as follows:

$$\begin{cases} \alpha = k_{p1}(v_t - v) + k_{i1}\int (v_t - v)\,dt \\ 0 \le \alpha \le \alpha_{\max} \end{cases} \quad (23)$$

where $\alpha_{\max}$ is the maximum opening of the throttle; v_t is the target speed; v is the actual speed; k_{p1} is the throttle controller proportional coefficient; k_{i1} is the throttle controller integral coefficient.

The brake controller is expressed as follows:

$$\begin{cases} F_\mu = k_{p2}(v_t - v) + k_{i2}\int (v_t - v)\,dt + k_{d2}\dfrac{d(v_t - v)}{dt} \\ 0 \le F_\mu \le F_{\mu\max} \end{cases} \quad (24)$$

where F_μ is the braking force; k_{p2} is the brake controller proportional coefficient; k_{i2} is the brake controller integral coefficient; k_{d2} is the brake controller differential coefficient; $F_{\mu\max}$ is the maximum braking force.

Some domestic economy cars was taken as the research object in this paper, the main performance parameters were as shown in table 6. The established model of the vehicle using Matlab/Simulink is shown in Fig.9.

Table 6 Main parameters of the vehicle

Parameter	Value
Total vehicle mass /kg	1050
Frontal area /m^2	1.9
Air resistance coefficient	0.30
Tire rolling radius /m	0.292
Rolling resistance coefficient	0.014
Main reduction gear ratio	3.94
Engine displacement /L	1.2
Maximum engine torque /N.m	115
Moment of inertia of the engine /kg.m^2	0.20
Moment of inertia of the clutch /kg.m^2	0.034
Transmission input shaft end of each gear inertia /kg.m^2	1] 0.0028 2] 0.0033 3] 0.0056

	4] 0.0086
	5] 0.0123
Each gear transmission output shaft rotational inertia /kgm^2	1] 0.54
	2] 0.24
	3] 0.16
	4] 0.13
	5] 0.11
Moment of inertia of the wheel /kg.m^2	125

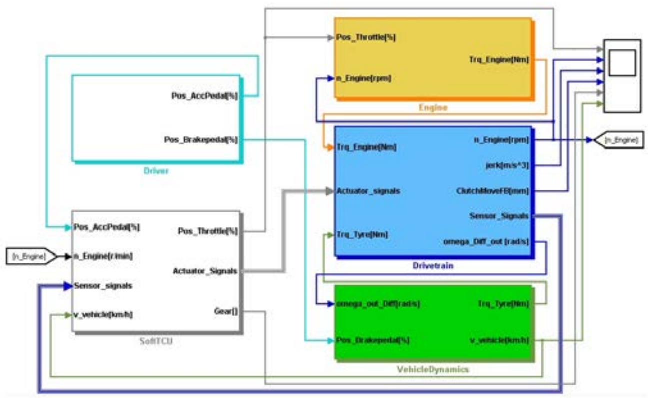

Fig.9. Established model of the vehicle using Matlab/Simulink

5.3 Simulation results and analysis

The vehicle speed curve and gear shift curve of vehicle with MAMT under a 15-condition are given in Fig.10. By comparison, it is found that the simulation speed is basically in agreement with the theory results. From the gear shifting curves, we can see that when the MAMT shifting from neutral gear to a new gear, there is transient zero moment in the shifting process curve, which conforms to the shifting specification.

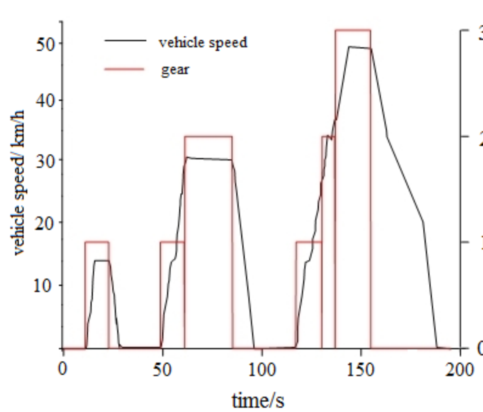

Fig.10. Simulation curve of the vehicle with MAMT under a 15-condition

The continuous upshift simulation curve of vehicle with MAMT with a throttle opening 80% is shown in Fig.11. The simulation results showed that it takes 14 seconds for the vehicle to accelerate to 100km/h, which agrees with the actual situation. The shift impact degree curve showed that the impact degree is maximal when magnetic powder clutch releases, the impact degree is minimal when magnetic powder clutch engages, the absolute value of impact degree is less than its maximum allowable value of 10m/s^{-3}, and that the shift quality is improved. The impact degree curve also indicates that the impact degree when clutch releases increases with the increase of speed, which is because the driving resistance and deceleration of the vehicle increase with the increase of the speed. The engagement impact degree of the magnetic powder clutch is maximal when the vehicle with MAMT starts, which is because the speed difference between the drive part and driven part of the magnetic powder clutch is great under the starting condition.

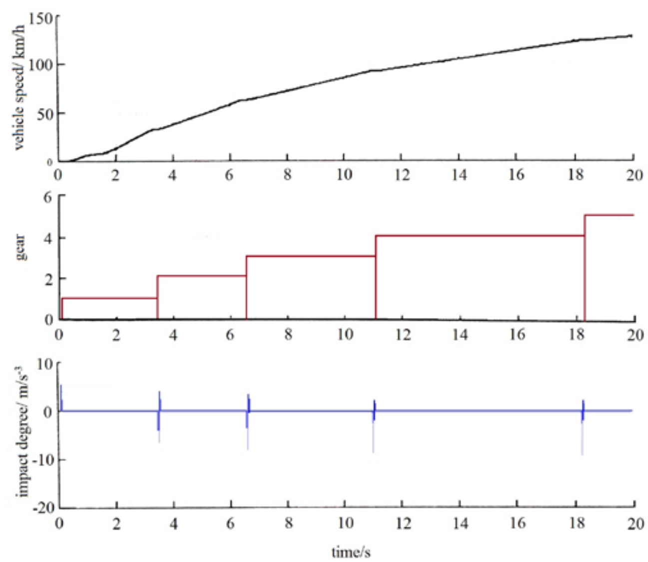

Fig.11. Continuous upshift simulation curve of vehicle with MAMT with a throttle opening 80%

The starting characteristics simulation curve of magnetic powder clutch under the starting condition with a throttle opening 80% was as shown in Fig.12. The simulation showed that the synchronization time of clutch is 1.3s, which is consistent with drivers' intent that the vehicle starts quickly when the throttle opening is large. And the compact degree under this condition can be controlled in the allowable range.

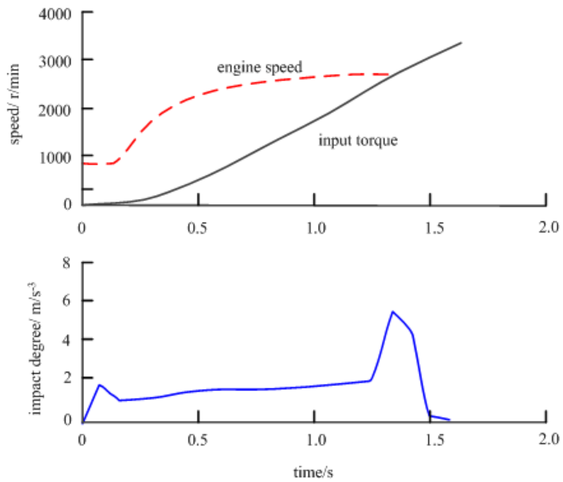

Fig.12. Starting characteristics simulation curve of magnetic powder clutch

The simulation curves of fundamental shift rules and comprehensive shift rules under the same condition were shown in Fig.13. The results showed that using the comprehensive rules can reduce shift frequency and unnecessary shift.

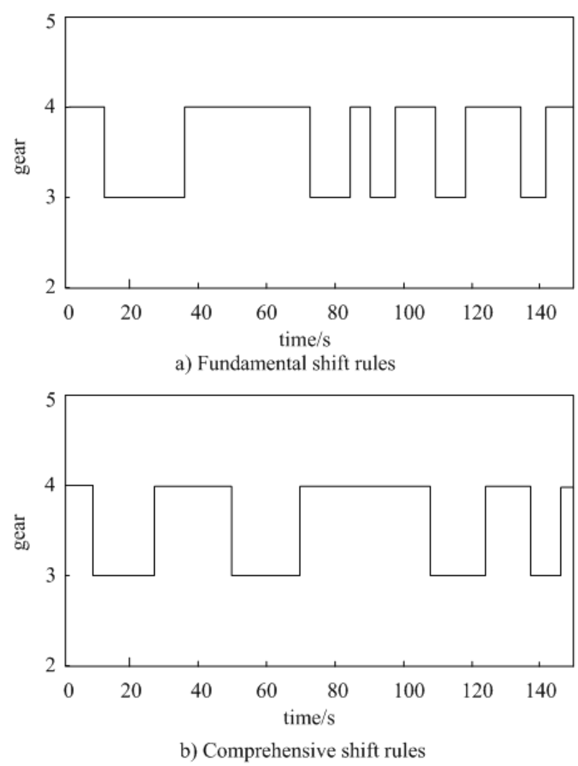

Fig.13.

6 Conclusions

In this paper, a new type AMT system with magnetic powder clutch (MAMT) was studied based on traditional AMT. The fuzzy controller for vehicle starting and the fuzzy controller for engagement control of magnetic powder clutch when vehicle shifting were designed in this paper. And the intelligent control of magnetic powder clutch was realized when vehicle starting, shifting and parking. The factors influencing the shift rules were analyzed. The comprehensive shift rules were formulated based on the fundamental shift rules. The simulation model of the whole vehicle with MAMT was built and simulated off-line. The simulation results showed that the intelligent control model of the magnetic powder clutch was accuracy and the comprehensive shift rules was effective.

Acknowledgements: This work was supported by Jiangsu Provincial University Natural Science Research Project of China (No. 12KJD580001).

References

[1] Wei Yingjun, Chang Siqin, Hu Pin. “Design and control of vehicle magnetic particle clutch”, [J] *Mechanical engineering*, v42, No.10, 2004, pp.12-14. In Chinese

[2] Watanabe, Tomoyuki. “Apparatus for controlling a magnetic particle clutch for use in a vehicle”. *United States Patent*, 4606446, 1986.

[3] Toshio Ttakano. “ELECTRO-MAGNETIC POWDER CLUTCH SYSTEM FOR AUTOMOBILES”. *United states patent*, 4403683, 1980

[4] Wang Shu. “A controllable vehicle magnetic particle clutch”. *China patent*, CN03222487.7, 2003

[5] Wang Cheng, Chang Siqin. “Structure and Performance Analysis of Vehicle Magnetic Particle Clutch”. [J] *Journal of Nanjing University of Science and Technology*, v36, No.5, 2012, pp.791-795. In Chinese.

[6] Wang Cheng, Chang Siqin. “Study on Effects of Magnetic Particle Properties on Performance of Magnetic Particle Clutch”. [J] *China Mechanical Engineering*, v 23, No.2, 2012, pp138-141. In Chinese.

[7] Wang Cheng, Chang Siqin. “Analysis and Design on Torque Performance of Magnetic Particle Clutch”. [J] *Transactions of the Chinese Society for Agricultural Machinery*, v42, No.10, 2011, pp.35-38,34. In Chinese.

[8] Wang Cheng, Chang Siqin. “Thermal Analysis and Test Reaearch of theMagnetic Powder Clutch for Vehicles”. [J] *WSEAS TRANSACTIONS ON APPLIED AND THEORETICAL MECHANICS*, v9, 2014, pp.35-344.

[9] Wei Yingjun, Chang Siqin. “Research on Fuzzy Control Technology Applied to Magnetic Powder Clutch during Vehicle Starting”.[J] *China Mechanical Engineering*, v16, No.11, 2005, pp.1029-1033. In Chinese

[10] Yan Yun-bing, Zhou Jian-peng, Chen Hua-ming. “Fuzzy Control and Smiulation for Transmission Process of Magnetic Powder Clutch during Shifting”.[J] *Tractor&Farm Transporter*, v37, No.3, 2010, pp.84-88. In Chinese

[11] Chang Siqin. *Vehicle Power Equipment*, China Machine Press, 2006.

[12] Li Yong, Chang Siqin, Wei Yingjun. “Shift Strategy of AMT Vehicle Based on Speed and Torque Control”. [J] *China Mechanical Engineering*, v 22, No.15, 2011, pp1880-1885. In Chinese.